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Spondylolysis and Spondylolisthesis: A Cost of Being an Erect Biped or a Clever Adaptation?

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ABSTRACT Spondylolysis refers to a separation in a vertebral arch between the body and the spinous process. Most spondylolysis seen in humans occurs in the lower lumbar region and is due to stress (fatigue) fracturing, usually through the isthmus between the superior and inferior articular processes. Referred to here as "typical" spondylolysis, it is related to erect posture and bipedal locomotion, and, as such, it is a uniquely hominid condition. It develops only after a child has begun to walk, and a developing lesion may heal or progress to complete separation. Seen more often in males than females, frequencies among populations vary widely. Certain activities have been suggested to put individuals performing them at greater risk to develop the condition. Although often approached as a pathological condition requiring corrective treatment, spondylolysis usually produces relatively mild symptoms if any at all, and may even provide the advantages of greater lower back flexibility. Complete bilateral spondylolysis separates the inferior articular processes from the body, thus allowing the body to slip forward relative to the vertebra below (spondylolisthesis). Another form of the condition, referred to as degenerative spondylolisthesis, allows a slow forward migration of one vertebra over another due to osteoarthritic remodeling of the posterior vertebral joints without any spondylolysis.

Spondylolysis and spondylolisthesis are conditions of the spine, almost exclusively the lower spine, that have intrigued anthropologists for at least a century. Spondylolysis is derived from two Greek roots, *spondylos,* referring to vertebra, and *lysis,* meaning dissolution (first usage attributed to Neugebauer, 1885). It gradually replaced an alternative term, spondyloschisis (vertebral cleavage, crack, or fissure), attributed to Poirier (Hitchcock, 1940), despite the fact that *schisis* (Greek) better describes the condition's most common etiology. Spondylolysis has come to refer to any separation that divides a hemi-arch, completely or incompletely, regardless of etiology. Defining it this way distinguishes it from spina bifida, separation in the midline caused by a failure of laminae (hemi-arches) to fuse with each other. Separate neural arch is sometimes substituted for spondylolysis, although a truly separate arch requires the defect to be complete through both hemi-arches (bilateral). The *olisthesis* in spondylolisthesis, also derived from Greek, means to slip or slide. It appears to have been used first by Kilian (1854) in reference to an anterior slippage of one vertebra relative to the vertebra below, and this usage has continued to the present.

In their classic form, spondylolysis and spondylolisthesis are uniquely human (hominid), related to habitual erect posture and the lumbar curve that makes it possible. Although the two conditions may be related, spondylolysis allowing spondylolisthesis to

take place, either condition frequently occurs without the other. They are thus separate and distinct phenomena, and it is important to treat them as such. It is also important to note that the terms as currently used are descriptive, not etiologic.

To understand the etiology of the two conditions and to avoid confusion still existing in the clinical as well as the anthropological literature, one must appreciate the history of research in this area and understand some of the ideas, frequently conflicting, that were advanced. Although their anatomical appearance is usually relatively simple and readily identifiable, subtle variations may hold clues to very different etiologies. Much time and print was spent in a search for "the cause" of spondylolysis, and cases representing very different etiologies were sometimes lumped together, as in pedigree studies, to produce confusing and sometimes erroneous results.

Despite what has turned out to be a far more complex picture than first surmised, the great majority of spondylolysis and spondylolisthesis cases seen archaeologically fall into only a few discrete categories: stress fracture ("typical") spondylolysis vs. atypical (congenital, traumatic, pathological) spondylolysis, and spondylolisthesis with separate arch vs. spondylolisthesis with intact arch (primarily degenerative olisthesis). This study will emphasize these most frequently occurring categories, while at the same time attempting to place them within the full range of etiologies represented by the two terms. Although spondylolisthesis predates spondylolysis as a recognizable clinical entity by several decades, the two conditions will be treated here in reverse order, recognizing their more common usage in anthropology as well as their order of occurrence when the two are related.

SPONDYLOLYSIS

The classic site of separation in spondylolysis is the isthmus between the superior and inferior articular processes, the so-called *pars interarticularis*. It is common practice to refer to this area simply as "the pars" ("the part"), terminology which could cause confusion if the context is not clearly established. The area is also referred to as "the isthmus," an "isthmic defect" being one through interarticularis. Other parts of a hemi-arch such as a pedicle may be affected, but such cases are relatively rare.

The recognition and study of spondylolysis began in the mid-1850s with a demonstration based on careful dissection and removal of all soft tissue by a Dr. Robert, working in Koblenz, and known to history simply as Robert zu Koblenz (Newell, 1995). He noted that it was impossible for a vertebra to slip forward under normal circumstances as long as its neural arch was intact (Robert, 1855). Only if the body was separated from the arch was it free to slip forward. This focused attention on the neural arch, specifically interarticularis, as the "cause" of the already well-known spondylolisthesis. Lambl (1858) confirmed that discontinuities in the arch did occasionally exist, and Hartmann (1865) confirmed that such discontinuities would allow a vertebral body to slip forward while the arch remained in place.

Investigation into the etiology of spondylolysis suggested maldevelopment, stress, and acute trauma as likely causes. Congenital ossification failure received considerable support in the mid-1800s after some reports suggested the presence of two ossification centers in each hemi-arch, creating the possibility that they could fail to unite (Schwegel, 1859; Rambaud and Renault, 1864). (This should not be confused with the two chondrification centers that do exist in each fetal hemi-arch.) Documentation of congenital etiology required demonstration that the condition was present at birth, with no later increase in frequency.

While Neugebauer's 1888 treatise on the subject, the most extensive to that date, acknowledged the congenital theory, he also suggested trauma as a cause, noting that anatomical preparations of spondylolysis sometimes presented the appearance of fracturing and patients' histories frequently included trauma. The fracture hypothesis had other supporters, Meyer-Burgdorff (1931) even suggesting that "all" spondylolysis was acquired. Kleinberg (1934) added that "in about half the cases that come to the surgeon's notice there is a distinct history of

trauma," but he could not demonstrate that the trauma produced the lysis. In fact, the well-corticated margins of the separation usually seen indicated that it existed long before a traumatic event brought it to a physician's attention.

For sake of clarification, spondylolysis will be divided here into two broad groups—typical and atypical, with typical spondylolysis accounting for the vast majority of cases observed archaeologically and clinically. Typical spondylolysis is relatively easy to observe, describe, and interpret, although all questions regarding its etiology have by no means been answered. However, it is the relatively small percentage of atypical spondylolysis cases, often lumped indiscriminately with the typical, that seems responsible for much of the confusion encountered over the years.

Typical spondylolysis

Skeletal anatomy. Typical spondylolysis is limited to the lumbosacral region, occurring with highest frequency in L5, less frequently in L4, and with significantly lower frequencies above this level and in S1. The distribution of affected vertebrae in a Canadian Thule/Historic Inuit series (Fig. 1) is typical in terms of the frequent involvement of L5 and L4, but perhaps atypical with respect to the relatively frequent involvement of vertebrae above and below this level. (Involvement of T4, where the defect is clearly congenital, is also atypical.) The separation ordinarily occurs through interarticularis, forming the so-called "isthmic" spondylolysis recognized by clinicians. Separation can range from barely detectable (Merbs, 1995) to complete, in which the hemi-arch is divided osteologically (a soft tissue connection usually being retained) into two parts. The most commonly observed example of spondylolysis, and the form observed most frequently in archaeological vertebrae, consists of complete, bilateral separation through interarticularis. The vertebra is thus separated into two parts: an anterior part consisting of the body, pedicles, transverse processes and superior articular processes, and a posterior part consisting of inferior articular processes, laminae and the spinous process (Fig. 2).

A broad range of variability can be observed. Separation may occur through a lamina, a pedicle, or between the superior and transverse articular processes. The separation site frequencies observed in the Canadian Inuit series (Fig. 3) are probably typical of populations generally, if the sample size is large enough. Separation through other than interarticularis virtually never occurs bilaterally, but may be paired with isthmic separation on the opposite side (Stewart, 1953). The separation may involve just one instead of both hemi-arches of a vertebra to produce unilateral spondylolysis (Vyhnánek and Stloukal, 1984a; Waldron, 1992). Separation on one side may combine with spina bifida to produce a separate hemi-arch, or bilateral separation may combine with spina bifida to produce hemi-arches that are divided from each other as well as from the body (Stewart, 1953).

The separation may be incomplete, looking like a crack extending from the superior or inferior margin of the isthmus into the bone (Merbs, 1989a, 1995). Although usually visible on the surface of bare bone as well as radiographically, some incomplete separations may be observed effectively only one way or the other. Complete separations may show considerable variability with respect to the anatomy of opposing edges at the defect site. The edges may be very irregular, but essentially match (complement) each other, giving the appearance of a recent fracture, or may have undergone significant modification, no longer resembling each other and having had no osseous contact whatsoever. This variable appearance, at least in part, is likely a function of time, but the time required for a vertebra to proceed from one end of the spectrum to the other and what factors other than time might control the change are difficult to identify.

Soft tissue appearance. In dealing with archaeological or other bare bone specimens one is faced with a distinct osseous separation. In the living, however, this gap is usually bridged by flexible connective tissue, the so-called "spondylolysis ligament," which is anchored deeply in the bone to either side

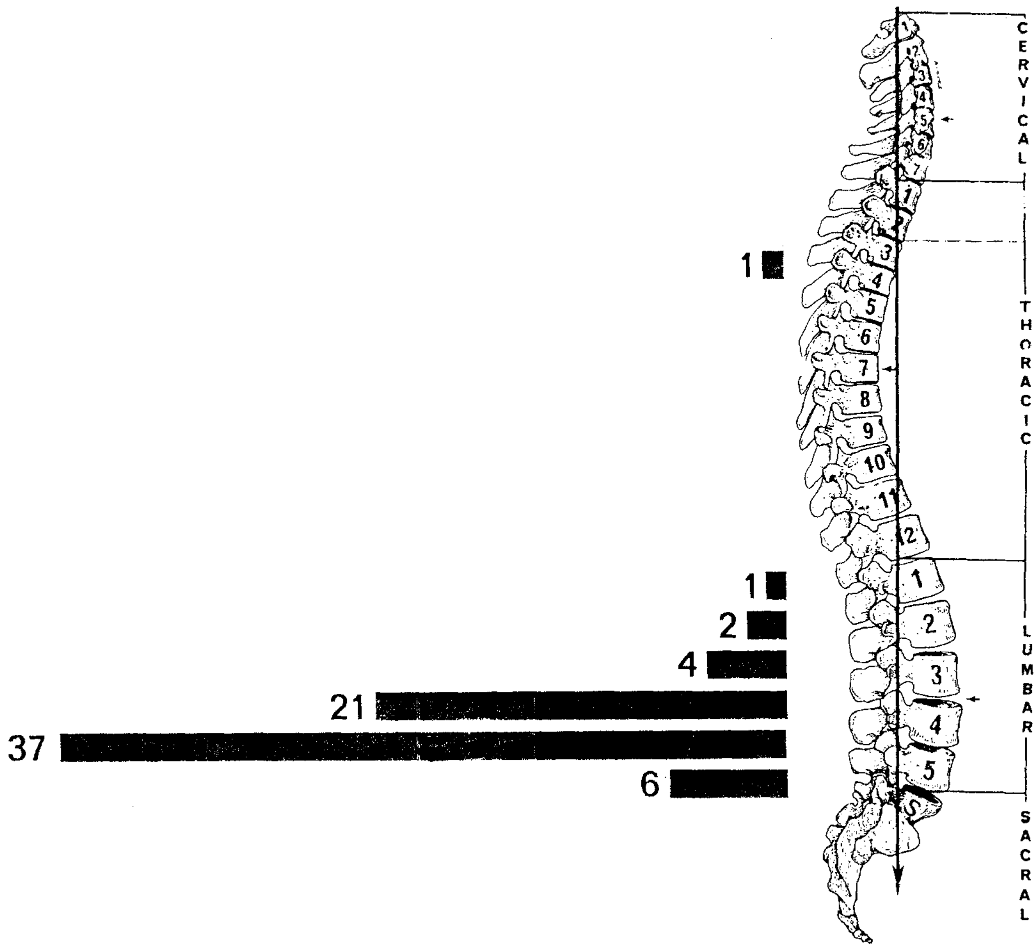

Fig. 1. Distribution of spondylolysis in the vertebral column of a Thule culture/Historic Inuit series from northwest of Hudson Bay, Northwest Territories, Canada. The case involving T4 is clearly congenital and those involving L1 and L2 may be congenital rather than due to stress fracturing. N = 72.

of the defect (Roche, 1949; Willis, 1931). The ligament is so tightly attached, in fact, that Eisenstein et al. (1994) experienced difficulty detaching it for experimentation. Considerable variability in the nature of this soft tissue connection apparently exists (Bosworth et al., 1955). Wiltse (1962) noted that if the bone ends were close together, they tended to be smooth, blunt, and eburnated, or even have hyaline cartilage covering the bone bordering the defect, presenting the appearance of a pseudo-arthrosis. If the gap was quite wide, the tissue in the defect was "more fibrous in nature" and "often normal ligaments seemed to fill the gap" (p. 547). The soft tissue connection between separated bone ends appears to change with time and perhaps with degree of separation, with a tough, flexible, ligamentous structure gradually replacing a bony one.

Sex. The great majority of spondylolysis studies, whether based on archaeological or anatomical collections, or general clinical surveys, have produced higher frequencies for males than females, with male frequencies sometimes being twice as high or even higher (Roche and Rowe, 1951; Stewart,

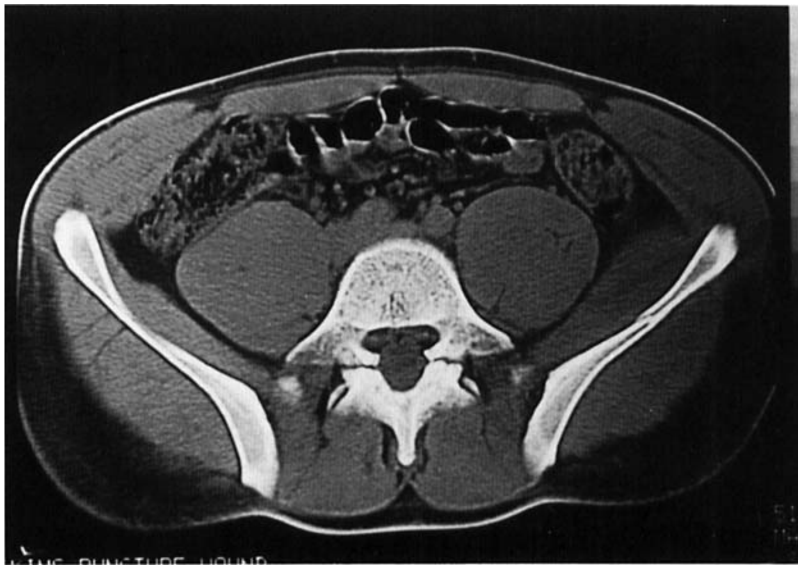

Fig. 2. CT scan of L5 showing complete, bilateral spondylolysis (separated arch) without olisthesis. The scan was taken following an episode of severe trauma that fractured the right ilium but the presence of spondylolysis had been identified several years previous to the trauma.

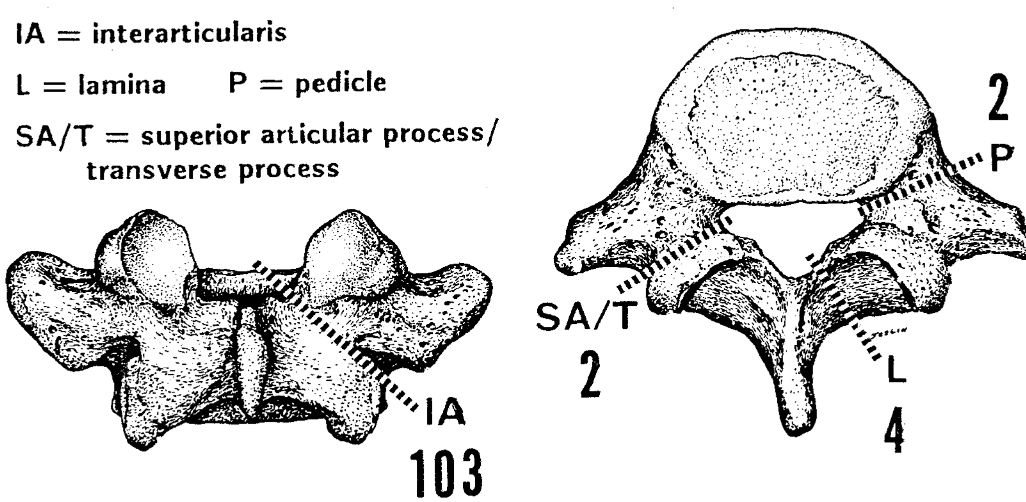

Fig. 3. Distribution of spondylolysis sites (hemi-arches affected) in the vertebrae in Thule culture/ Historic Inuit series from northwest of Hudson Bay, Northwest Territories, Canada. One laminar and three interarticularis cases are more likely of congenital origin rather than due to stress fracturing. N = 111.

1953, 1979; Gunness-Hey, 1982; Bradtmiller, 1984; Fredrickson et al., 1984; Virta et al., 1992). Exceptions to this are Bridges' (1989) study of Archaic Indians from northwestern Alabama and a study of Eskimos from Point Hope (Tigara), Alaska, by Lester and Shapiro (1968), but in each case the difference found was less than 5%.

Age. An important key to understanding the etiology of typical spondylolysis is the age of affected individuals. This of course is age at death in archaeological cases, but even in clinical cases, except in rare instances where patients are being closely monitored radiographically (usually for some other condition), it is the age at which the spondylolysis was discovered rather than the age it occurred that is revealed. In both archaeological and clinical contexts, however, incomplete separation may reasonably be interpreted as bone activity taking place at the defect site.

Examinations of fetuses, neonates, and very young children have never revealed the presence of typical spondylolysis at birth (Batts, 1939; Fredrickson et al., 1984; Rowe and Roche, 1953). Although Borkow and Kleiger (1971) reported a case involving L4 in a newborn, the presence of other, clearly congenital deformities suggest that this is actually an example of "atypical spondylolysis," of quite different etiology. A case was reported in a 3-month-old infant (Borkow and Kleiger, 1971), but this individual had been born with a back deformity that had not been carefully examined at birth. Spondylolysis was also described in infants 8, 10, 16, and 18 months of age (Friberg, 1939; Villiaumey, 1968; Laurent and Österman, 1969; McKee et al., 1971; Pfeil, 1971; Wiltse et al., 1975), but it is not clear if other musculoskeletal abnormalities were present as well. It was also reported in a 17-month-old child that had been walking only a few weeks (Kleinberg, 1934), but this was long past birth, and the case was complicated by the presence of a dislocated hip and the probability that the olisthesis was due to separation through the pedicles rather than interarticularis.

Testing the hypothesis that spondylolysis resulted from two ossification centers (instead of one) in each hemi-arch failing to fuse, Batts (1939) studied 200 fetal spines ranging in age from 3 months to full term and found a second center in just one hemi-arch. Hadley (1955) found just one center per hemi-arch in the 50 spines of fetuses and neonates he studied. Although these studies suggest that congenital spondylolysis resulting from multiple hemi-arch ossification centers, or even division of a single center as suggested by Willis (1931), could occur, such an extremely rare phenomenon cannot account for the vast majority of arch defects observed. Nevertheless, the congenital hypothesis received considerable support through the 1920s (Turner and Tchirkin, 1925) and 1930s (Junghanns, 1931; Schmorl, 1932; Brocher, 1938; Friberg, 1939), and is occasionally cited even today (Schwartz, 1995).

Poirier (1911) attributed spondylolysis chiefly to mechanical effects associated with the attainment of erect posture. Typical is the case of a girl who, because she suffered from histiocytosis X, was examined at 7.5 months of age, at 13 months when she first began to walk, and five more times during the following 18 months, with spondylolysis becoming evident only on the last set of radiographs (Wertzberger and Peterson, 1980). The condition thus appears to be closely related to the assumption of erect posture and bipedal locomotion (Batts, 1939; Hitchcock, 1940; Hadley, 1955; Hensinger, 1989). Rosenberg et al. (1981) were unable to find it in 143 adults who never were able to walk upright. When compared to the 5.8% frequency in the general population, according to the authors, this finding is significant at the $P < 0.001$ level. Spondylolysis, at least in its classic form, appears to be a uniquely hominid condition (Neugebauer, 1885, 1888; Thieme, 1950).

Clinical studies suggest that presently the most common age of onset is 5–6 years of age, with frequency increasing to age 20, and then remaining constant after that age (Rowe and Roche, 1953; Baker and McHollick, 1956; Fredrickson et al., 1984; Hensinger, 1989). It might therefore be termed "a condition of youth." The archaeological picture, however, suggests a later age of onset, examples of affected children being quite rare. Lester and Shapiro (1968) found an affected 5-year-old, but only five subadult cases overall, in material from Point Hope, Alaska. Gunness-Hey (1982) found only two (5.4%) examples in subadults from Kodiak Island, Alaska, compared with 31.1% in adults. Stewart (1953) found spondylolysis in one of 23 (4.3%) Alaskan children up to 6 years of age, in three of 26 (11.5%) children

7 to 12 years of age, and in 10 of 69 (14.5%) adolescents 13 to 18 years of age. The youngest example found in an Inuit series from Southampton Island, Northwest Territories, Canada, was approximately 15 years of age (Merbs, 1983). Separation in this case was complete, but unilateral, with callus present suggesting that the lesion site had still been active when the individual died. The youngest case in Archaic Indians from Alabama was an 18- to 20-year-old male, and the youngest female affected was over 40 years of age (Bridges, 1989). The 6- to 15-year age group tends to be poorly represented in archaeological skeletal series generally, and it is doubtful that it has been examined with sufficient rigor, particularly for early (incomplete) stages of spondylolysis. Nevertheless, the extreme rarity of spondylolysis observations among individuals dying during childhood and early adolescence in ancient groups probably represents a real phenomenon which stands in contrast to the present-day clinical picture.

The frequency among adults in archaeological series is variable. It is uncertain if small sample size or different methods of determining age at death are factors. Stewart (1953) found an increase from age 19 to 40 in Alaskan Eskimos, with no increase beyond 40, while Lester and Shapiro (1968) found a gradual increase at Point Hope, even beyond age 45. Bradtmiller (1984) found the frequency to increase through age 49 years at two South Dakota Arikara sites before sharply decreasing. These and other studies are at least consistent in showing increases in frequency beyond age 20, in some instances rather significant increases. This again varies from the general clinical picture.

The Canadian Inuit study that included incomplete lysis (Merbs, 1995) was somewhat more consistent with that seen clinically, at least with respect to adolescents and young adults. The youngest individual observed with spondylolysis was already 12–15 years of age, and the defect was still incomplete and unilateral. Incomplete lysis was limited almost entirely to the two younger age groups, accounting for 100% (5/5) of all lysis sites in adolescents and 53% (26/49) in young adults, but only 5% (3/56) in middle and old adults. The overall frequency of spondylolysis doubled from adolescence to early adulthood (20–30 years) in this study, almost equally divided between complete and incomplete in the young adults. This suggests a pattern in which incomplete lysis in adolescents, particularly in the lower lumbar region, progressed to complete lysis during early adulthood, with many new cases of incomplete lysis developing, particularly in the mid-lumbar and sacral regions. Middle adults (30–45 years) resembled the young adults in the frequency of complete lysis, but the almost total lack of incomplete lysis in this group suggests the possibility that most complete cases in young adults would continue as such into middle adulthood, while most incomplete cases of young adulthood would heal. The presence of bone callus at some of the incomplete fracture sites suggests that an attempt at healing had been underway when death intervened. A further reduction in frequency after age 45 in the Canadian Inuit suggests that even complete lysis can heal, particularly if the condition remains unilateral and severe olisthesis has not occurred. The reduction in frequency observed in older age groups in some archaeological studies could actually be due to healing instead of simply an artifact of sample size or preservation.

Population studies. Published observations of spondylolysis in archaeological contexts go back to the 1880s and 1890s in the work of Ten Kate, Sergi, and Martin in southern South America. During the first two decades of this century Matiega noted its presence in skeletons from Santa Rosa Island and near Santa Barbara, California, and Hrdlička in skeletons from New Jersey, Arkansas and Louisiana (Stewart, 1931). Congdon (1932) found “separate neural arch” in ten (5%) of 200 Native American skeletons from the Columbia River region that he described in excellent detail. Eleven of the 12 affected vertebrae were L4 or L5, the exception being a sacrum (S1). In one case, the separation on the left side is said to have occurred between the superior articular and transverse processes (rather than through interarticularis).

Information on other groups around the

world became available primarily through the study of anatomical collections. Japanese data were provided by Adachi, Hasabe, and Taguchi (Stewart, 1931). Shore (1929) described a case of spondylolysis with extreme spondylolisthesis (total displacement) in the skeleton of a South African Bantu, following it with four more typical cases from the same series (Shore, 1930). East African spondylolysis was reported by Allbrook (1955), and Eisenstein (1978) provided more information on South Africa, adding European-African data to that from Bantu. Frequencies of spondylolysis are reported for African-Americans and European-Americans, derived from the Terry Collection at the U.S. National Museum of Natural History, Washington, D.C., and the Hamman-Todd Collection at Case Western Reserve University, Cleveland, Ohio (Roche and Rowe, 1951).

The highest frequencies of spondylolysis appear to be those found in Eskimos (Stewart, 1931, 1953; Lester and Shapiro, 1968; Gunness-Hey, 1982; Simper, 1986; Merbs, 1983, 1995, 1996). Stewart (1931:61) attributed this to "the inbreeding of an isolated group," but later he (1953) cited unusual posture as a possible cause. Relatively high frequencies have also been reported for some American Indian groups such as Archaic Indians from Indian Knoll, Kentucky (Snow, 1948) and Alabama (Bridges, 1989), and Plains Arikara from South Dakota (Bradtmiller, 1984). Very ancient cases of spondylolysis have been reported for 4,000-year-old Maritime Archaic skeletons from Port au Choix, Newfoundland, Canada (Anderson, 1976), and a 3,000–4,000-year-old La Jollan woman from Punta Minitas, Baja California, Mexico (Merbs, 1980). Frequencies have also been published for ancient skeletons from the Aleutian Islands, Alaska (Yesner, 1981), British Columbia (Cybulski, 1992), and Arizona (Miles, 1975), as well as for Lapps (Schreiner, 1931), Romano-British and Anglo-Saxons (Waldron, 1991), Slavic and Slavic-Avaric populations in central Europe (Vyhnánek and Stloukal, 1984a), ancient Lithuanians (Jankauskas, 1994), and many other archaeological series. Although marked frequency differences and interesting variations have sometimes been noted in these studies, their significance is often difficult to interpret, particularly as varying criteria were used to collect the data, descriptions are incomplete, and age, sex and other relevant data may be missing.

Stress fracturing. Although the implication that spondylolysis was most often due to stress is certainly present in some of the earliest literature (Lane, 1885; Neugebauer, 1888; Barclay-Smith, 1911; Poirier, 1911), Roberts (1947) was the first to clearly attribute it specifically to stress (fatigue) fracturing. Supporting the fatigue fracture hypothesis was the observation of incomplete or partial lysis on radiographs of patients (Maldague and Malghem, 1976; Drevet et al., 1990) and directly on bare bone (Stewart, 1953; Merbs, 1983, 1995). Especially convincing are longitudinal studies showing lesion changes through time, some proceeding to complete separation (Hadley, 1963; Klinghoffer and Murdock, 1982), while others underwent spontaneous repair (Rabushka et al., 1973; Wiltse et al., 1975; Silvello and Vercellesi, 1980).

Experimental studies of the lumbosacral region and factors that might lead to spondylolysis have been carried out using live subjects, cadavers, simulated anatomical specimens, computer simulations, and the mathematics of biomechanics. Early it was discovered that although the interarticular isthmus is narrow, it is unusually strong (Krenz and Troup, 1973). The application of considerable force was necessary to cause fracturing (Hutton et al., 1977).

Farfan et al. (1976) utilized vertebral anatomy and electromyography to examine stresses occurring in lumbar vertebrae when various forces were applied. They felt that flexion overload, unbalanced shear forces, and forced rotation were all capable of producing isthmic defects. The situation is further complicated by the fact that all three types of overload could be applied simultaneously and in various combinations. Of all the forces acting on the lumbar spine, they felt that torsional violence was most likely to disrupt the neural arch.

Utilizing cadavers in a study designed to test which activities were most likely to cause spondylolysis, Green et al. (1994) mea-

sured bending forces at interarticularis on lumbar vertebrae during simulated flexion and extension movements, with and without high compressive forces. Motion segments were loaded to simulate full flexion, full extension, high compression in flexed posture, and high compression in lordotic posture. The authors concluded that full extension posed a greater threat than full flexion, and that compressive loading had little effect. The likelihood of stress fracturing would be especially great in activities that required alternating forward and backward bending of the lumbar spine, because this would involve frequent and large stress reversals at interarticularis.

The overall conclusion from these studies seems to be that although it has proven possible to produce spondylolysis experimentally through the application of enormous force, this may not be significant to the usual etiology of the condition. An unusual source of support comes from a study of so-called "jumpers' fractures," injuries to the thoracolumbar spine associated with vertical plunges. Only 23 of 72 fractures in 38 individuals involved the arch, and only two of these affected L4 or L5 (Smith et al., 1977). Even then, the two fractured lumbar arches had undergone fusion prior to the trauma, making this region unusually rigid and vulnerable to fracture. In other words, acute trauma involving the lower back does not usually produce spondylolysis. Rather, it is fatigue loading through the isthmus that ultimately results in stress fracturing and isthmic spondylolysis. Not much seems to be known about the actual mechanics of this kind of fracturing. However, Farfan et al. (1976) favor the theory that the defect is due to a single episode of overload which induces the initial microfracture. Repeated overloads promote non-union and allow for possible progression to complete separation.

Early stages of fracturing. If the condition is indeed a kind of stress or fatigue fracture, as it is specifically labeled by most researchers today (Wiltse et al., 1975), it should occasionally be identifiable as a partial fracture before it progresses to complete separation. Stress fractures characteristically have a "sub-radiological" period during which radiographs will appear normal (Elliott et al., 1988). Their presence may be detected using forms of imaging that visualize bone activity at a particular site. Bellah et al. (1991) found an abnormal focus of radiotracer uptake in the lumbar spines of 71 of 162 young patients (44%) with symptoms of low-back pain possibly related to spondylolysis, using single photon emission computed tomography (SPECT). In 66 of these, the abnormalities appeared in the lower lumbar region localized to interarticularis. Although abnormalities were visible on standard radiographs or computed tomographs (CT) for a few of these individuals, the great majority (75%) showed no detectable radiographic changes. Weir and Smith (1989) were able to follow for several months a 12-year-old male who complained of low back pain, aggravated by athletic activity. Radiographs were normal, but bone scan showed increase in radionuclide uptake at interarticularis of L5, predominantly the left. Six months later the pain worsened and radiographs showed bilateral spondylolysis of L5, without olisthesis. This illustrates that bone imaging utilizing radioactive emissions may suggest early presence of spondylolysis, but verification (distinguishing it from other conditions) requires standard radiography, CT, or magnetic resonance imaging, or visualization of bare bone.

Despite obvious difficulties faced in identifying minute defects using standard radiographs in clinical practice, examples have been noted. Drevet et al. (1990), for example, were able to identify 23 clinical cases of partial lysis involving interarticularis, 15 in pre-adults and eight in adults. Standard radiography was adequate for diagnosis in 19 cases; tomography was required in four. Initial radiological signs were defined as cortical "notches," more often affecting the lower margin than the upper one. Maldague and Malghem (1976) observed "partial cracks" at interarticularis in 20 patients, five times as an isolated finding, and 15 on the side opposite a complete unilateral separation. They describe the défect as occurring on the inferior border near the pedicle.

Archaeological collections and the opportunity they present for observing bare bone would appear ideal for detecting the early

stages of spondylolytic stress fracturing, but until recently little was done other than an occasional acknowledgement of their presence (Stewart, 1953; Merbs, 1983). A study of Canadian Inuit skeletons provided interesting new data on this aspect of the condition, the observation of 34 examples of incomplete lysis in a total of 110 hemi-arches with spondylolysis (Merbs, 1995). Defect lengths range from barely discernible (2 mm) to approximately 60% of the diameter of the isthmus. Some of the incomplete lesions extend from the superior margin of the isthmus inferolaterally into the bone; some extend from the inferior margin superomedially. Occasionally both margins are affected simultaneously, or the superior margin is affected on one side and the inferior on the other. Most occurred at the margin of the isthmus, but some affecting the superior margin began medial to the isthmus, several millimeters from the superior articular process. The most extreme of these could more accurately be described as laminar rather than isthmic. Given their trajectory at time of death, some of the incomplete separations noted in the Inuit study might easily have proceeded through the pedicle or between the superior and transverse articular processes as through interarticularis. The final trajectory, had the person lived, might have been determined by relatively small biomechanical variables. An interesting variation observed by Vyhnánek and Stloukal (1984b), in which the separation forms an angle, might be explained in terms of defects proceeding from the two margins simultaneously (as in the Inuit study), each with a different trajectory. It is interesting to note that although all incomplete separations observed radiographically in the Inuit study were also visible superficially on the bare bone, the reverse was not always true (Merbs, 1995). This was despite the radiographic advantages available when dealing with archaeological specimens rather than living patients: positioning the object for the best possible view, using soft radiation, and extending exposure time for maximum clarity. It further emphasizes the difficulty faced by clinicians in observing the earliest stages of spondylolysis in their patients.

The picture that emerges is one of mechanical stress in the lumbosacral region, created in a vertebra by movement relative to that below, producing a stress fracture. The fracturing begins with bone activity detectable using radioactive emission imaging, but undetectable radiographically. It develops to the level where it can be detected in bare bone and, finally, on standard radiographs. At this level cases may produce minimal pain, if any, as most are found only by accident or in systematic surveys. The 60% maximum lesion noted in the Canadian Inuit study (Merbs, 1995) suggests that lesions of greater than this magnitude may be so unstable that they proceed rapidly to complete separation.

Sacral involvement. A special case in this process, one that has been only reported archaeologically (Barclay-Smith, 1911; Congdon, 1932; Merbs, 1983, 1996), is spondylolysis of the first sacral vertebra (S1). Given the necessity of movement occurring between the affected vertebra and the vertebra below to produce a stress fracture, it is clear that S1 spondylolysis must have occurred prior to the fusion of S1 with S2. It appears significant that all but two of the 16 cases of S1 spondylolysis reported for Alaskan and Canadian Inuit involve young adults, approximately 18 to 20 years of age (Merbs, 1996). It also seems significant that 15 of the 16 affected were male, the sex that shows later skeletal maturation as well as likely engaging in activities placing greater stress on the lower back, such as harpoon throwing, kayak paddling, and weight lifting.

Healing. Presence of spondylolysis on radiographs at one point followed by absence on later radiographs has been interpreted as healing (Jackson and Wiltse, 1974; Wiltse et al., 1975; Maldague and Malghem, 1976; Cyron and Hutton, 1978; Gainor et al., 1983; Letts et al., 1986; Cope, 1988). In some cases the healed lysis had been incomplete. In others, however, it had already proceeded to complete separation and even to minor olisthesis (Fig. 4).

Although limited to the condition as it appeared at time of death, the study of archaeological cases also suggests that spondylolysis can heal. The age distribution of S1 spondy-

Fig. 4. Healed case of complete, bilateral separation (separate arch) which healed after mild olisthesis (anatomy specimen).

lolysis in Inuit indicates that lesions active during late adolescence or early adulthood healed to become undetectable in later adulthood (Merbs, 1996). Similarly, the relatively high frequency of lumbosacral incomplete separation in Canadian Inuit among adolescents and young adults, and near total absence of incomplete separation in older adults (with no increase in complete separation), strongly suggests that many of the early, incomplete cases had simply healed (Merbs, 1995). The presence of bone callus around some of the defects also suggests a healing process.

Attempts to associate spondylolysis with other conditions have produced interesting if not always convincing or understandable results. First is the association of lysis with spina bifida, an association apparently more likely to be found in young clinical patients (Fredrickson et al., 1984) than in older archaeological skeletons (Waldron, 1993). Age may well be a key factor here in terms of when patients are examined and how old individuals are when they die. Depending on age, spina bifida at a particular vertebral site may be normal, and even if closure is abnormally delayed, it may eventually occur. The association when first noted clinically was interpreted by some as strengthening the congenital etiology theory for spondylolysis, spina bifida clearly being a congenital condition. Spina bifida was also observed to frequently accompany cervical spondylolysis, also a clearly congenital condition. However, spina bifida's relationship to stress fracture spondylolysis may be quite different, being entirely mechanical, the laminar cleft weakening the arch and thus making it more susceptible to separation (Merbs, 1983). It is interesting to note that Suezawa et al. (1980), in their study of lower lumbar vertebrae from cadavers, were able to initiate a fracture of the isthmus by means of force applied in a transverse direction only after they simulated spina bifida by splitting the arch.

An association between spondylolysis and bone mineral loss was observed by Thompson et al. (1985), but here the relationship appears to be inverse. Based on a study of Canadian Inuit skeletons, individuals with high bone mineral levels seemed more susceptible to spondylolysis while those with low bone mineral suffered compression fractures of vertebral bodies. In other words, the osteoporotic vertebral body appears to have absorbed shocks and thus served as a kind of buffer for the isthmus. There is potential for age bias here, however, as spondylolysis is more likely to be found in younger individuals while bone mineral loss and vertebral compression fracturing are associated with older individuals.

Familial nature. Although the familial nature of spondylolysis and spondylolisthesis was established very early (Bakke, 1931; George, 1939; Bailey, 1947; Toland, 1955; Baker and McHollick, 1956; Wiltse, 1957), studies have tended to confuse the picture by considering the two conditions interchangeable, or grouping conditions with very different etiologies such as lumbosacral isthmic separations and dysplastic olisthesis. It is not surprising, then, that the results have tended to be confusing and even contradictory, the condition seen as a recessive trait by some (Wiltse, 1962) and a dominant trait by others (Amuso and Mankin, 1967; Haukipuro et al., 1978; Shahriaree et al., 1979). "Incomplete penetrance" has been suggested

to explain some of the discrepancies observed (Wynne-Davies and Scott, 1979), and lack of penetrance as high as 75% has even been suggested (Haukipuro et al., 1978). These studies seem a long way from pinning down a "spondylolysis gene" (Haukipuro et al., 1978). It is interesting and probably significant, however, that dysplastic olisthesis produces a stronger family association than olisthesis due to isthmic spondylolysis when the two are separated in studies.

Despite some design problems in these studies, they do demonstrate that even "stress fracture spondylolysis" follows a familial pattern that likely has some basis in genetics. What is being inherited, however, is obviously not the defect itself, but features of vertebral anatomy that increase the risk of isthmus fracturing. Determining the nature of these anatomical features, however, has proven difficult. Anatomical studies have searched for especially weak arches, elements that could physically impinge on an arch, or features that could increase the stresses an arch would have to sustain. Suggested indications of weakness included an arch that was unusually narrow somewhere along its length (sometimes even referred as "pre-lysis") or contained an unusually large vascular foramen. However, it has not been demonstrated that either of these features makes an arch more susceptible to separation (Allbrook, 1955; Miles, 1975; Magora and Schwartz, 1980). Meyer-Burgdorff (1931) noted how the inferior articular process of a vertebra above and the superior articular process of a vertebra below could impinge on an isthmus, and Nathan (1959) felt that spondylolysis could result from this pincers action. However, impingement would more likely occur in older individuals when disc space is reduced, whereas spondylolysis is a condition more likely to develop in youth. Furthermore, partial separations look like fractures, not like the isthmus was being pinched (Merbs, 1995).

A longer presacral spine, an acutely inclined top sacral surface, increased lumbar curvature, and reduced depth and curvature of the superior sacral articular facets have been suggested as anatomical features likely to put place greater stress on arches. Although Stewart (1956) found no significantly greater frequency of spondylolysis in Alaskan Eskimos with these features compared with those lacking them, he observed that small differences did consistently favor this pattern. Inclination of the superior sacral surface was also measured on radiographs by Peterson et al. (1990) and a significantly greater angle was found in males with spondylolysis compared to those without. Their very small female sample, however, showed no such relationship. Although a greater angle could increase the effect of gravity on the stresses experienced by the isthmus, Peterson et al. (1990) warn that the angle could actually be an effect rather than a cause of spondylolysis.

Testing whether transitional lumbosacral vertebrae are more susceptible to spondylolysis has produced mixed results, perhaps partly because sample sizes have been very small and partly because the direction of shift at this border has not always been considered (Merbs, 1974). Any increase (or decrease) in spondylolysis frequency could be affected simply by the unusual anatomy of the transitional vertebra, or by an increase in pre-sacral length associated specifically with caudal border shifting (lumbarization). Elster (1989) found only a slightly higher frequency of spondylolysis (5%, 7/140) in individuals with transitional vertebrae than in those without (4%, 78/1,860), and he did not identify the direction of shift. Merbs (1983) found three of six (50%) L6 vertebrae (caudal shift) in his Sadlermiut Inuit study to have spondylolysis, compared with 10% of L5 (8/83) and L4 (8/81). Stewart (1932, 1956), however, found no such association and felt that an extra vertebra and separate arch may "occur in the same individual only by chance" (p. 135, from 1932). This interesting question remains unresolved.

Activity relationship. Beyond relating spondylolysis to erect posture and bipedal locomotion, studies have associated higher frequencies of the condition with specific postures and activities that concentrate abnormal stress in the lumbosacral region. Lane (1886) observed that spondylolysis occurred most frequently "in people doing heavy labor," and Friberg (1939) noted that those engaged in strenuous work showed

symptoms earlier and more frequently than those doing light work, which could explain the greater frequency usually seen in males. Reporting on multiple spondylolysis in the skeleton of a young adult female from Egypt, Barclay-Smith (1911) attributed the condition to "excessive mechanical usage" that commenced at a fairly early age. He even suggested that the affected individual may have been a contortionist who "delighted Ptolemaic audiences as an expert exponent of the acrobatic art" (p. 171). Stewart (1953) felt that the unusual posture of Eskimos, specifically hyperextension of the lower back, put them at greater risk. This would seem to fit with results obtained by Green et al. (1994) regarding stresses caused by full extension of the back. In the clinical literature, spondylolysis appears to occur with higher frequencies in individuals engaged in activities that involve repetitious, vigorous movements of the lower back, particularly hyperextension, activities such as gymnastics (Jackson et al., 1976; Goldberg, 1980; Hooper, 1984; Ciullo and Jackson, 1985; Bozdech and Dukek, 1986; Letts et al., 1986; Commandre et al., 1988; Green et al., 1994), contortionism (Steinbück and Springorum, 1980), dancing (Micheli, 1983; Bejjani, 1987), diving (Rossi and Dragoni, 1990), hockey (Letts et al., 1986), javelin throwing (Feldmeier et al., 1985; Bejjani, 1987; Chapman, 1987), rowing (Stallard, 1980) canoeing (Jakab, 1989), handball (Hoshina, 1980), weight lifting (Kotani et al., 1971; Granhed and Morelli, 1988; Risser, 1991), wrestling (Rossi and Dragoni, 1990), playing lineman in football (Ferguson et al., 1974; Alexander, 1985; McCarroll et al., 1986) and fast bowling in cricket (Green et al., 1994).

Pain. Spondylolysis may be associated with pain, but separating pain due to lysis from that due to olisthesis has been difficult, and generally the clinical literature has made little effort to do so. Pain due specifically to spondylolysis would presumably refer directly to the fracturing. Stress fractures certainly can be very painful, enough to severely alter an individual's normal activity patterns, and back pain may be responsible for spondylolysis coming to the attention of a physician initially. Much of the time, however, the discovery is accidental, with any pain produced not considered severe enough to require special treatment. In their study of living Alaskan Eskimos, Kettelkamp and Wright (1971) note that 50% of those with spondylolysis complained of lower back pain, while 27% of those without lysis had similar complaints. Individual pain thresholds may vary significantly, and most lower back pain appears unrelated to spondylolysis. It has proven very difficult to correlate complaints of back pain intensity with degree of pathology observed (Libson et al., 1982). Eisenstein et al. (1994) note that symptoms of disabling low back pain appear in a minority of individuals with spondylolysis, usually for the first time in adulthood. They examined the "spondylolysis ligament" as a possible pain source. Dissecting out the ligament, innervating it, and investigating it immunohistochemically, they concluded that it could possibly be a source of pain.

Greater flexibility. Separation of the arch has for so long been considered pathology that any advantages it might confer have received little attention. Given the substantial nature of the soft tissue connection that develops after separation, the condition might instead be viewed as a kind of adaptation to the human condition, where a rigid bony connection is replaced by a flexible ligamentous one (Merbs, 1989b). Hensinger (1983) noted that "children with spondylolisthesis appear to have more flexibility or looseness at the L5–S1 junction" (p. 144), and that the increased mobility is even reflected in the anatomic appearance of the column in such individuals, the upper surface of S1 being convex rather than flat. However, this change appears to be effect rather than cause, with the initiating factor being spondylolysis. Effect rather than cause also appears to explain the observation of Bird et al. (1980) that adults with spondylolisthesis (nearly all degenerative rather than isthmic) considered themselves more supple in youth than adults without olisthesis. Nevertheless, one cannot help wonder how often this greater suppleness resulted from spondylolysis that later healed, leading eventually to degenerative olisthesis. It

might prove interesting to investigate the importance of lower back flexibility in various cultures, particularly those associated with high frequencies of spondylolysis.

Atypical spondylolysis

Atypical spondylolysis as considered here is classified primarily on the basis of etiology, with appearance usually reflecting the etiology. Included is spondylolysis due to a congenital deformity, severe trauma, or pathology which severely weakens or actually destroys the connection between the neural arch and the body. Taken together, these atypical forms make up a very small percentage of all spondylolysis cases observed.

Congenital spondylolysis. Congenital spondylolysis is best known in the cervical region but has been reported for all parts of the column. It must be noted that the congenital etiology here is usually so obvious that some authors do not even label it spondylolysis, either because they are unfamiliar with the broad definition of the term, or to avoid confusion with the far better known stress fracture condition in the lower back. Although clearly resulting from a developmental ossification error, the point of defect is not located where a separation between developing ossification centers normally exists, as in spina bifida. The situation in congenital spondylolysis is generally more complex and requires knowledge of earlier stages of development for explanation.

Credit for the first case of true congenital spondylolysis described in the clinical literature goes to Hadley (1946). This was a 35-year-old man who was thrown from his car when it struck a tree. Routine x-ray checkup disclosed that C5 was missing its left pedicle, the C4 pedicle was more slender than normal, and other minor variations existed in the general vicinity. Hadley felt that the condition had been present since birth, probably produced no pain, and was discovered incidental to a post-accident checkup.

Cervical. Although more cases of congenital cervical spondylolysis were described, it appears to be a relatively unusual phenomenon. In a recent survey of the clinical literature, Poggi et al. (1992) report 89 cervical vertebrae with spondylolysis in 81 individuals. The vertebrae affected in order of frequency were: C6 = 56, C2 = 15, C4 = 11, C5 = 5, and C3 = 2, with no C1 or C7 involvement. The lesions were bilateral in 54 affected vertebrae, unilateral in 26 (15 left, 10 right, and one unspecified), and not noted for nine. Poggi et al. (1992) refer to the defects simply as involving "pars interarticularis." However, their exact location is not always clear from the radiographs or descriptions provided in the original reports, but often it clearly is not interarticularis. The anatomy of cervical vertebrae is very different from that of lumbar vertebrae, the cervical interarticularis being a short, broad pillar, not the long, narrow isthmus seen in the lumbar region. The cervical hiatus may actually occur anterior to the pillar, i.e., through a pedicle (Wilson and Norell, 1966), through a pillar (Black et al., 1991), or dorsal to the pillar, i.e., through a lamina (Koyama et al., 1986). In some cases an entire lamina or arch can be missing (Kirchmer and Sarwar, 1977). Cervical spondylolysis is frequently accompanied by spina bifida and dysplasia of the affected or adjacent vertebrae, and Poggi et al. (1992) observed that 50 of 88 affected individuals also had at least mild spondylolisthesis. Affected males outnumbered females 50 to 23 (sex was not specified in the remaining eight cases). Although the most common presenting symptom was neck pain, the spondylolysis was often found incidentally during a checkup for something completely unrelated.

Morvan et al. (1984), noting that the condition had never been seen in an infant, proposed that cervical spondylolysis was caused by repetitive microtrauma resulting in stress fractures similar to the process producing typical lumbosacral separation. Against this view and strongly in favor of a developmental etiology, however, are the following: the very different anatomy and stress patterning found in the cervical region, the absence of any reports of incomplete separation indicative of stress fracturing in this region, and the frequent presence of other developmental conditions in affected individuals. Although 28 of the 81 cases reviewed by Poggi et al. (1992) had a history of head or neck trauma preceding the onset of symptoms, radiographs showed well-corti-

cated margins at the site of the defect, thus eliminating recent fracture as a possibility. More likely, an instability that existed as a result of the defect was exacerbated by the trauma with neck pain and other symptoms resulting. Although the challenge of Morvan et al. (1984) to find this condition in an infant remains to be met, enough is now known about the development of a vertebra relative to this defect to strongly support the statement by Poggi et al. (1992) that the term cervical spondylolysis describes a long-standing congenital defect.

Embryologically, a cervical vertebra develops from six chondrification centers (Sherk and Parke, 1989). The cartilaginous centrum forms from two of these centers, which initially develop on either side of the notochord before uniting. Another pair develops on either side of the neural tube and later fuse to form the dorsal part of the neural arch and spinous process, and the last two develop between the dorsal pair and the centrum to ultimately form the ventral part of the arch (pedicle, transverse process and articular processes). Cervical spondylolysis appears to be a union failure of chondrification centers forming the centrum and ventral part of an arch (pedicle defect) or the ventral and dorsal parts of an arch (defect dorsal to the articular pillar). Enchondral ossification cannot occur across the defect and an osteological deficiency results. It is important to keep in mind that this is a chondrification deficiency, not an ossification deficiency. It is also important to view cervical spondylolysis not as a specific entity like typical lumbosacral spondylolysis, but as part of a cluster of anatomical features which include spina bifida and several kinds of dysplasia such as thinning of the affected region, with complete separation being just an extreme case of dysplastic thinning.

No descriptions of archaeological examples of cervical spondylolysis involving the pedicle or articular pillar could be located, but cases where all or part of an arch have failed to form have been published. Collins (1986) notes a case from the Keōpū Burial Site in Hawaii involving a 25- to 30-year-old female in which the right lamina and half of the spinous process of C5 is missing, as is the left lamina and half of the spinous process of C6, along with fusion of C2–3, spina bifida of C7, and digital, costal, and dental malformations. The existing hemiarches of C5 and C6 curved down and up, respectively, to form a relatively normal appearing neural arch that protected the spinal cord. An atlas with arch completely missing dorsal to the articular pillars was reported for a 50- to 55-year-old female dating to the 15th to 17th centuries AD from the Alytus burial ground in Lithuania (Jankauskas, 1994).

Thoracic. Spondylolysis of the thoracic spine is very rare, or at least has gone unrecognized by clinicians. Tomsick et al. (1974) describe two cases, both involving 19-year-old men, in which a right pedicle is missing in T8 in one individual and T11 in the other. The etiology here seems analogous to that described for the cervical region. Allbrook (1955) reports spondylolysis in T3 (two cases), T5 and T12 in the columns of East Africans, but provided no details or photographs. Jankauskas (1994) also reported unilateral (right) spondylolysis of T2 in a 40- to 45-year-old male from the Cathedral of Vilnius, Lithuania, dated to the 16th to 18th centuries AD. The defect here is through interarticularis, but its superior end extends to the midline of the markedly asymmetrical arch. Based on location, general appearance, and absence of the stresses that cause fracturing in the lower back, this case is identified here as atypical, and likely congenital.

Sacral. Three examples of sacral spondylolysis of likely congenital etiology were discovered by Rowe (1950) among 1,548 skeletons in the Terry Collection. All three were African-American, two males and a female, and all showed other abnormalities in the lower lumbar-sacral region. Wells (1963) added a similar case involving a male(?) of unknown origin in an anatomy collection at the University of Cape Town, South Africa. The etiology in these cases appears to be a deficiency involving cartilage development, similar to that described for the cervical region.

Lumbar. Based on the extremely low frequencies of congenital spondylolysis seen in other regions and the relatively high frequency of typical spondylolysis found in the lumbar region, convincing examples of con-

genital spondylolysis in this region may be difficult to identify. Possible keys to their discovery may lie in the appearance of the defect, the presence of other vertebral anomalies in the same general vicinity, and the part of the vertebra column affected. Perhaps the most convincing examples of congenital lumbar spondylolysis are those which show aplasia of a pedicle, with hypoplasia probably representing a less severe form of the same phenomenon (Normal and Johnson, 1973; Morin and Palacios, 1974). Wells (1963) illustrated a fifth lumbar from a Bantu skeleton at the University of Witwatersrand, Johannesburg, South Africa, that has an unusually narrow, poorly formed pedicle with a gap midway along its length. The L4 from an Egyptian described by Barclay-Smith (1911) matches this description. In both cases the vertebra is markedly asymmetrical and a chondrification deficiency etiology seems likely. Five curious clinical cases were described by Verhaak (1974) in which a pair of vertebrae (L3–4, L4–5 twice, and L5–6 twice) had failed to segment unilaterally (hemi-block vertebra). An arch defect in the lower of the pair was due to that portion of the arch being present but failing to separate from the vertebra above. The etiology here was clearly congenital.

Spondylolysis of L1 or L2, although not common, has fascinated researchers encountering it because its appearance is often so different from that seen lower in the lumbar column. Usually the defect extends through interarticularis, but also through much of the adjacent lamina, its upper end terminating near the midpoint of the arch (Stewart, 1953). Although the medial part of the separation has irregular edges, the lateral part presents what appear to be faceted surfaces opposing each other across the gap (Stewart, 1953; Nathan, 1959; Merbs, 1983). While faceting certainly suggests a moveable joint, determining when and under what circumstances the parts were movable, if ever, has proven elusive. Although upper lumbar spondylolysis has generally been lumped with lower lumbar involvement as caused by stress fracturing (Lowe et al., 1987), the lack or near absence of the prerequisite stresses in this region makes this questionable (Allbrook, 1957; Nathan, 1959; Cyron and Hutton, 1978). Reporting on 11 cases involving spondylolysis of L1 (4), L2 (5), and L3 (2) in which the clinical picture strongly resembles that reported for archaeological specimens, Miki et al. (1991) are convinced that the etiology is congenital rather than traumatic, although they do not attempt to explain it further. Again, this may be an error of chondrification rather than ossification.

Spondylolysis caused by acute trauma. Another category of atypical spondylolysis with respect to etiology is that caused by acute trauma, generally of considerable intensity. If the fracturing is limited to interarticularis it may appear indistinguishable from that caused by progressive stress fracturing. In other cases the fracturing will be more extensive and thus more easily identifiable, and it may produce retrolisthesis (posterior slippage) rather than spondylolisthesis (Griffin and Sutherland, 1980; Cohn et al., 1989). It should be noted that the so-called hangman's fracture produces a spondylolysis, usually perimortem, of C2 (Wood-Jones, 1913; Gehweiler et al., 1977; Pepin and Hawkins, 1981; Parisi et al., 1991; Starr and Eismont, 1993). Convincing cases of spondylolysis resulting from acute trauma, without obvious fracturing of other parts of the vertebra, are infrequent in the medical literature (Serre, 1956; Gérard, 1962; Ferris and Hutton, 1983; Cope, 1988; Markel and Graziano, 1992). Some healed spontaneously (Wiltse et al., 1976). Such cases are likely to be rare in the anthropological context and very difficult to distinguish from stress fracture (complete) spondylolysis.

Pathological spondylolysis. In pathological spondylolysis the separation occurs in a vertebra already severely weakened by pathology, as in osteopetrosis (Albers-Schönberg disease) (Szappanos et al., 1988) or osteogenesis imperfecta (Rask, 1979). It could also include situations where pathology directly causes the separation, as with brucellosis (Rajapakse et al., 1987), tuberculosis (Fig. 5), or metastatic carcinoma, but in this situation the lysis is clearly secondary to the

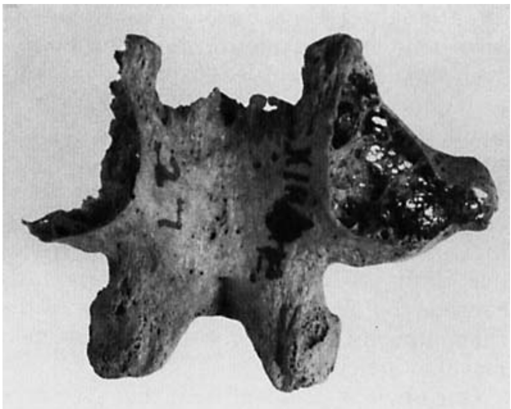

Fig. 5. Pathological spondylolysis in a lumbar vertebra from the Hochelaga site, Quebec, Canada (ventral view of arch). The pathology that destroyed the pedicles was probably tuberculosis.

pathology and probably would not be singled out for special consideration.

SPONDYLOLISTHESIS

Cases of extreme anterior vertebral slipping and their potential for causing obstruction during childbirth (Herbiniaux, 1782) led to recognition of spondylolisthesis many years before spondylolysis (Newman and Stone, 1963; Newell, 1995). Although Roasenda (1958) attributes the first actual medical descriptions of spondylolisthesis to Kiwisch and Seifert of Prague in the early 1850s, first use of the term is generally attributed to Kilian (Newell, 1995) describing four cases in 1854.

Clinical classification

The classification system for spondylolisthesis in general use by clinicians today is basically that proposed by Wiltse et al. in 1976 (updated by Wiltse and Rothman, 1989). It was designed specifically for clinicians working with live patients, and its application to bare bones poses some problems. Six basic categories are recognized: I. Congenital; II. Isthmic; III. Degenerative; IV. Traumatic; V. Pathological; and VI. Postsurgical.

Congenital (I). As defined by this system congenital spondylolisthesis is attributed to congenital anomalies occurring in the affected region, which the authors unfortunately limit to the "lumbosacral junction" (Wiltse and Rothman, 1989). Three subtypes are recognized. Subtype I-A refers to dysplastic axially oriented zygaphophyseal facets, "usually combined with spina bifida," and subtype I-B to facets that are sagittally oriented. Subtype I-C appears to be a general category for anomalies that do not fit into I-A or I-B (e.g., congenital kyphosis). The system was probably more useful to the paleopathologist with respect to Type I in its earlier version (Wiltse et al., 1976), where essentially two subtypes were identified, though not actually labeled as such. In the first subtype, olisthesis was related to an actual separation of congenital origin, while in the second, it occurred without lysis due to the anomalous anatomy of the isthmus, zygapophysis, or other part of the arch. An elongated isthmus could result in olisthesis, for example, or poorly developed joints could result in an olisthesis produced by subluxation or disarticulation.

Isthmic spondylolisthesis (II). This category is related specifically to a fracturing of interarticularis. Two subtypes are recognized. Type II-A, labeled "lytic," associates the olisthesis specifically with a stress fracture, while II-B associates it with elongation but non-separation of the isthmus. The elongation is presumably due to repeated fatigue microfractures. This type thus combines a specific etiology, stress fracturing, with a specific anatomical location, the isthmus. This can be seen as a strength in the sense that it accounts for the vast majority of cases likely to be encountered by both the clinician and the paleopathologist (at least in younger individuals). It is also a weakness, however, in the sense that it excludes stress-fracturing spondylolysis in parts of the arch other than the isthmus. Simply referring to this type as "stress fracture spondylolisthesis," regardless of the part affected, would solve much of the problem, although some etiologic difficulties remain as discussed below. Separating congenital elongation (I) from stress-fracture elongation (II) could hopefully be accomplished using radiographs, but

this situation may be so rare in archaeological material that this is not a problem.

Degenerative spondylolisthesis (III). Probably the least problematic of the types, degenerative spondylolisthesis is attributed to a "long standing intersegmental instability" (Wiltse et al., 1976:25). Osteoarthritic remodeling of the zygapophyses allows forward slippage with no spondylolysis, a condition that may actually be easier to observe in archaeological cases than those encountered by the clinician.

Traumatic spondylolisthesis (IV). This category is attributed to severe trauma. Any part of the neural arch other than interarticularis (e.g., fractured pedicle) is affected. This type is attributed to severe trauma, and, in the experience of Wiltse et al. (1976:26), "has always healed with immobilization." Their elimination of "acute fracture dislocation" from this type seems unnecessary, particularly when they add that "the pathology may be virtually the same" (Wiltse and Rothman, 1989:85). Severe trauma may often include fractures in parts of a vertebra not associated with lysis or olisthesis, such as the body or transverse process, but it can also include separation of an articular process, usually an inferior process. This kind of separation does not divide the arch itself, but it does separate the body from the "bony hook" that holds it in place, thus allowing olisthesis to occur. Technically speaking, this is olisthesis without spondylolysis, or at least without lysis in the usual sense, but the effect can be the same.

Pathological spondylolisthesis (V). Pathological spondylolisthesis is attributed to generalized (subtype A) or localized (subtype B) pathological changes which may be congenital (e.g., Kuskokwim syndrome) or acquired later in life (e.g., infectious disease). There appears to be overlap here between types I and V with respect to congenital conditions.

Postsurgical spondylolisthesis (VI). Included in type V as "spondylolysis *aquisita*" in the earlier version of the system (Wiltse et al., 1976), postsurgical spondylolisthesis refers to a fatigue separation occurring after intentional vertebral fusion. As such it is an iatrogenic stress fracture, and perhaps as such should be a subtype of type II. Unlikely to be encountered by paleopathologists, it could nevertheless be of forensic significance, and it also contributes to a better understanding of how stresses in the lower back lead to fracturing. Perhaps not surprisingly, surgical fusion of a separated arch does not eliminate the stresses that originally caused the fracturing, but simply shifts them upward (or downward), to the next movable articulation.

One obvious problem with this system is that it mixes anatomical description with etiology. Good, thorough description must come first, etiology subsequently being associated with description whenever possible. The first obvious descriptive division in spondylolisthesis is that between olisthesis with separated neural arch and olisthesis with intact arch. In the first, the biomechanics involved are relatively straightforward, even if the etiology of the separation is not; in the second both the biomechanics and the etiology may be more difficult to identify.

Spondylolisthesis with separate neural arch

Anterior slippage is ordinarily prevented in the vertebral column by the inferior articular processes (referred to as the "bony hook") which firmly hold a vertebra in place relative to the one below. It that hook becomes disconnected from the anterior part of the vertebra, it is only the connective tissue, basically the intervertebral disc and ligaments, that holds the affected vertebra in place. The potential for anterior slippage is particularly great in the lower lumbosacral region, where the bodies are ventrally oriented downward and gravity can work upon them. The degree of olisthesis occurring varies greatly from one individual to another, ranging from none, or barely detectable, to complete, where the body of the affected vertebra slips completely off that of the vertebra below. Reporting on 160 cases of spondylolisthesis, Harris (1959) found that no slippage had occurred in 37.5%, slippage of less than one-third the anteroposterior diameter of the vertebral body below occurred in 52%, greater than one-third in 8%, and complete

displacement in 2.5%. Shore (1929) described a case of complete displacement of L5 relative to S1 following separation of the arch in L1 in the skeleton of a 42-year-old South African Bantu woman.

Spondylolisthesis usually seems to occur at or soon after the "hook" becomes separated, becoming stable for the remainder of the person's lifetime, or slipping may occur again later in life, perhaps in direct response to trauma (Fredrickson et al., 1984; Oakley and Carty, 1984; Danielson et al., 1991). In any event, the slippage is more likely to be episodic than gradual. Why olisthesis varies so widely from one individual to another probably depends on multiple factors such as degree of laxity of the discs and ligaments, the plane of the affected vertebral body, and stresses to which the region is subjected, including acute trauma. Spondylolisthesis following arch separation has been observed and even measured in archaeological specimens (Congdon, 1932; Miles, 1975; Merbs, 1980, 1983), but no systematic study seems to exist.

An obvious impediment to further slippage would be if the disc at the level of the olisthesis were to ossify, thus fusing the bodies together. This appears to be a rare event, not surprisingly since olisthesis usually produces less rather than more stability at the site, making it unlikely that the immobilization necessary for fusion could take place. An interesting example of fusion following olisthesis was observed in an adult female from Bright Angel Ruin, an Anasazi site located at the bottom of Grand Canyon, Arizona (Merbs and Euler, 1985). Complete isthmic separation had occurred in L5, leading to an olisthesis of 15 mm relative to S1, or slightly more than one-third the anteroposterior diameter of the sacral body. The L5–S1 disc then solidly ossified, fusing the two vertebral bodies and producing a permanent record of the olisthesis. Two other cases of vertebral fusion that resulted in a permanent record of olisthesis were found in Anglo-Saxon skeletons from England (Manchester, 1982).

Spondylolisthesis without separate arch

Spondylolisthesis without spondylolysis, or more precisely, "with bony hook intact," may be due to various factors. The three most likely are osteoarthritic remodeling of the zygapophyses, subluxation or disarticulation of the zygapophyses, or lengthening of the connection (interarticularis or pedicle) between the hook and the body.

Degenerative spondylolisthesis. The term degenerative spondylolisthesis, first used by Newman (1955), turned out to be descriptive and specific enough to gain wide popularity. Its cause is clearly severe osteoarthritis (osteoarthrosis) of the zygapophyseal joints, resulting in a forward migration of the joints. The temptation is thus to see the condition, particularly when considered entirely in its osteological context, as merely a severe form of osteoarthritis affecting the lower back. Clinicians usually accord degenerative olisthesis a separate status because zygapophyseal osteoarthritis, even when severe, does not necessarily result in olisthesis, and because the condition is associated with a specific cluster of symptoms. Degenerative spondylolisthesis has been observed in the cervical region (Potter and Norcross, 1954; Deburge et al., 1995), but is much better known as a lumbosacral phenomenon.

Population parameters. Degenerative olisthesis has been observed primarily in older adults, usually not before the age of 40 (Rosenberg, 1975; Bolesta and Bohlman, 1989; Herron and Trippi, 1989; Takahashi et al., 1990). Most patients are in their 60s before they first bring the condition to the attention of their physician (Rosenberg, 1975; Epstein et al., 1983; Brown and Lockwood, 1983). It occurs more frequently in women than in men (Rosenberg, 1975; Bolesta and Bohlman, 1989), the actual ratio varying from as low as two to one (Epstein et al., 1983) to as high as six to one (Herron and Trippi, 1989). Because of the age factor, variable symptoms, and complicating conditions, overall frequency values are difficult to determine. Potter and Norcross (1954) found only 19 affected individuals in a review of radiographs from 3,000 individuals, but their sample was skewed heavily in favor of the population segment least likely to show the condition—young males. Degenerative olisthesis is more common in blacks

than in whites (Rosenberg, 1975; Bolesta and Bohlman, 1989); other population comparisons are unavailable. Partial or complete sacralization of the L5 vertebral body (cranial shift) occurred four times more commonly in individuals with degenerative olisthesis than in the normal population (Herron and Trippi, 1989).

In a clinical study involving 200 patients with degenerative olisthesis, level involvement was: L3–4, 8%; L4–5, 80%; and L5–S1, 11% (Rosenberg, 1975). It was also found in 20 skeletons of the Hamman-Todd Collection, 17 (9%) females and 3 (1.6%) males; L4–5 was involved 18 times and L3–4 twice (Rosenberg, 1975). Other studies confirm that this pattern of level involvement, with 80% of cases occurring at L4–5, is typical, but it contrasts with a study by Merbs et al. (1994) showing the L5–S1 level more commonly affected (90%) than L4–5 in the ancient American Southwest. Stewart (1935) reported two cases of olisthesis without lysis involving L5–S1, one from Hooper Bay, Alaska, and one from Hawikuh (Zuni), New Mexico, and a third case involving L4–5 from Nunivak Island, Alaska.

Degree of olisthesis. Because the neural arch remains intact in degenerative spondylolisthesis, the maximum amount of slippage possible is considerably less than that following arch separation. Based on the percentage of anteroposterior vertebral body diameter exposed by the olisthesis (Laurent and Österman, 1976), a maximum slippage of approximately 30% is usually cited (Rosenberg, 1975; Herron and Trippi, 1989). However, one case of 43% slippage was reported by Postacchini and Perugia (1991), and Rosenberg (1976) illustrated a case where the affected vertebrae (L4–5) fused in an olisthetic position of approximately 40%. At the minimum end of the scale, olisthesis of less than 5% is often excluded from studies because of difficulty in making such small measurements (2 mm) on radiographs (Rosenberg, 1975).

Unilateral spondylolysis. An interesting variant of degenerative spondylolisthesis is the situation where complete spondylolysis has occurred on just one side with a thickening ("sclerosis" on radiographs) on the opposite side (Sherman et al., 1977; Albers and Yochum, 1980; Aland et al., 1986; Gunzburg and Wagner, 1988; Waldron, 1992). Slippage allowed by the lysis on one side produces greater stress on the opposite, intact side, leading to degenerative changes that can result in olisthesis (Kornberg, 1988). To be precise, this condition would have to be called olisthesis with lysis on one side and degenerative olisthesis on the other, or perhaps "olisthesis with partially intact hook.".

Retrolisthesis. Zygapophyseal degeneration can also produce retrolisthesis (posterior slippage). Based on a study of 57 cases (Rothman et al., 1985), however, the pattern of degenerative retrolisthesis is very different. Males are affected more than females (60% to 40%), and the vertebral level involved tends to be higher, with L3–4 accounting for 33% of cases and L4–5 only 27%. Involvement of L1–2 and L2–3 also occurred, and two or more levels were more frequently affected. Degree of slippage tended to be less, with 69% of patients showing 3 mm of slippage or less, 32% between 4 mm to 6 mm, and none more than 6 mm. However, zygapophyseal remodeling was observable in less than 18% of cases, while disc involvement was common. This suggests that retrolisthesis may be more a manifestation of disc degeneration and narrowing than joint degeneration (Rothman et al., 1985). Since this is basically a phenomenon of soft tissue, its identification in archaeological skeletons would present a challenge.

Other causes. Spondylolisthesis resulting from zygapophyseal subluxation may be due to inadequate development or pathological alteration of a joint, or extreme mechanical factors (e.g., from severe trauma). Olisthesis resulting from joint developmental problems are generally subsumed under the heading "dysplastic" in the clinical literature, with many forms of dysplasia lumped together or combined with spondylolysis. Dislocation spondylolisthesis due to severe trauma appears to be quite rare, and at least as likely to produce retrolisthesis as anterior slippage (Griffin and Sutherland, 1980; Edvardsen, 1983; Cohn et al., 1989).

Spondylolisthesis caused by a lengthening of the interarticular isthmus or pedicle is usually associated with more general developmental problems such as seen in arthrogryposis (Kuskokwim syndrome) or Rubinstein-Taybi syndrome (Wright, 1970; Robson et al., 1980). Although frequently noted in the clinical literature, the reported presence of at least some degree of separation suggests that the elongation is usually due not to an abnormal growth process (Lorenz, 1982; Ishikawa et al., 1994), but to repeated fracturing, separation, and healing of the affected part (Corrigan, 1984).

Pain. Spondylolisthesis may produce local or general pain. In degenerative olisthesis much of the pain can be localized to the pathological zygapophyses, or to accompanying disc degeneration. Stenosis (narrowing) of the neural canal and lateral nerve openings could lead to nerve compression and symptoms involving the lower extremity (Postacchini and Perugia, 1991). Despite some reports of extreme pain and even disability associated with this condition, it is interesting to note that lower extremity symptoms had sometimes been present for 10 years, with varying degrees of back pain existing even longer, before individuals felt compelled to present themselves for treatment (Epstein et al., 1983). Spondylolisthesis associated with arch separation could also produce local pain, but not associated specifically with the zygapophyses. Nerve impingement could also produce symptoms in the lower extremities similar to those noted for degenerative olisthesis. However, attempts to correlate degree of slippage with intensity of symptoms have achieved limited success (Birch et al., 1986). Even in cases brought to the attention of the clinician through pain in the lower back, there is some question whether the pain was actually caused by the olisthesis, or whether the occurrence of the pain and the vertebral problem in the same individual was merely coincidental (Schmorl and Junghanns, 1968). Related pain may be less likely if the olisthesis develops during childhood rather than afterward (Rossi, 1978; Gainor et al., 1983). Spondylolisthesis has received more blame for lower back and lower extremity pain than it probably deserves.

Spondylolisthesis in chickens

Spondylolisthesis (without arch separation) is found in another biped, the broiler chicken. The vertebral column of the chicken is very different from that in humans, however, consisting of 14 cervical, 7 thoracic, 14 lumbosacral, and 6 coccygeal vertebrae. Of these, only T1 and T6 have superior and inferior articular processes that form diarthrodial joints with the vertebrae above and below; T2 through T7 are fused amphiarthrodial joints, and T7 is fused with all lumbar, sacral and coccygeal vertebrae. Although involvement of T1 has been reported (Khan et al., 1977), the traditional site of the problem is T6, due primarily to the shock absorber nature of this vertebra (Wise, 1970). Although both chickens and humans are subject to spondylolisthesis, the factors which determine the condition in the two species show little overlap. Both creatures are bipeds, but the vertebral column in chickens is basically horizontal rather than vertical as in humans. In neither case is the olisthesis likely to be congenital. While in humans it usually is related to spondylolysis or arthritic joint remodeling, in chickens it appears related to increasing T5–7 lordosis.

CONCLUSIONS

Spondylolysis and spondylolisthesis have fascinated as well as confused orthopedists, anthropologists and other researchers for more than a century, but only in the last several decades has any real understanding of them emerged. Part of the difficulty lay with the terminology itself, the two terms often being used interchangeably, part with imprecise description, and part with a failure to realize that the terms were descriptive, not etiologic. Some of the popularity of spondylolysis among anthropologists clearly derives from its interesting evolutionary significance, being a uniquely hominid condition (chickens excepted). More, however, comes from its being viewed as an "osteological trait" that could be used when comparing one skeletal series with another. Its presence or absence in a skeleton seemed difficult to miss, and it was hard to confuse with any-

thing else. It if were a congenital condition, some genetic basis could be implied, and it could then be included with other so-called discontinuous variables seen in the skeleton and used to measure phenetic distances among populations. On the other hand, if it were not genetically determined and not congenital, but reflected biomechanical stresses produced by behavior, it might be useful for reconstructing activity patterns of past populations. Typical spondylolysis does not lend itself easily to either interpretation, although overall it certainly fits far better with the second than the first. At least its biomechanics are now reasonably understood—any genetic basis is not.

It is now clear that spondylolysis in the broad use of that term can sometimes be congenital, either localized or as part of a syndrome. Congenital spondylolysis is best known in the cervical region but can occur anywhere in the column. To understand the etiology of this form one must understand the development of a vertebra, with chondrification patterns usually of greater relevance than ossification patterns. This form may be useful in population studies or in tracing ancient lineages. However, it appears to account for a very small proportion of all spondylolysis observed, particularly when cases occurring outside the region of L3–S1 are removed. Similarly, cases caused (or allowed) by pathology or severe trauma represent a minute and readily identifiable percentage.

The focus is then directed to the region where the stresses of erect posture are concentrated (L3–S1), and where various activities can exacerbate the situation. The evidence that the typical spondylolytic lesion here is a stress fracture is now overwhelming. Imaging techniques and visual observation (in the case of archaeological specimens) has allowed the lesion to be observed at all stages. The developing lesion need not progress to complete separation, and many actually heal. This gives the condition a dynamic quality, making it more difficult for an anthropologist working with dead people, as "population frequencies" can change relative to age at death.

Although even lumbo-sacral stress-fracture spondylolysis may follow a familial pattern indicating that some anatomical features make their owners more susceptible to the condition, its presence clearly has much more biomechanical and behavioral than genetic significance. To what extent, then, can spondylolysis tell us something about past activity patterns? Sports medicine studies show individuals engaging in some kinds of activities have higher frequencies of spondylolysis than other activities, and have attempted to identify specific aspects the activities that could put participants at greater risk. Although such studies have produced generally consistent results, the data have not been tested for statistical significance. Biomechanical studies have also attempted to identify elements of sporting activities likely to place greatest stress on interarticularis. Although they demonstrate that complete fractures are easily produced under conditions of extremely heavy loading, producing stress fractures in the bone-like substance is very difficult. Some interesting facts have emerged, one being that hyperextension of the lower column puts greater stress on the isthmus and is thus more likely to cause fracturing than flexion, even under heavy loading. How precisely any spondylolysis seen in archaeological specimens may be related to a specific activity remains to be seen, but it is certainly an area deserving of continued investigation.

Spondylolisthesis with arch separation is an interesting subject, which presents obvious difficulties when dealing with ancient skeletons. It becomes detectable only after secondary anatomical alterations have taken place. Attribution of pain and or disability, as well as any obstetric obstruction it might cause in women, appears greatly overrated. However, it certainly remains an interesting element in studying health profiles of individuals of the past (Merbs and Euler, 1985).

Although well-known in the clinical context, spondylolisthesis without arch separation, or without any spondylolysis at all, is not well-known to anthropologists. Like spondylolysis, however, lumbosacral involvement appears to be a uniquely hominid condition, and one likely related to erect posture and specific activities. Unlike spondylolysis, however, which is a condition of

youth, degenerative spondylolisthesis is a condition of "mature" adults. Why the level of involvement appears to vary so sharply between Native American skeletons (L5–S1 = ca. 90%) and clinical observations (L4–5 = ca. 80%) (Merbs et al., 1994) remains to be explained.

The study of spondylolysis and spondylolisthesis in ancient populations should continue, and is included in the standards for data collection (Buikstra and Ubelaker, 1994). Observations should be careful, precise and complete. They should include the entire column, not just the lumbar region, and they should include subtle manifestations, such as the earliest stages of fracturing, not just complete separation. Studies should be augmented with radiography and other imaging techniques whenever possible. Speculation regarding an etiology other than stress fracturing in the case of lumbosacral spondylolysis, or severe osteoarthritis in the case of olisthesis without lysis, should be based solidly on description and reasonable interpretation. Early literature on the subject should be approached with caution.

The "lysis" part of spondylolysis is clearly a misnomer, except in the minute number of pathological cases where "lysis" actually occurs. Shall we continue to use this venerable term despite its etiological inaccuracy or should it be renamed? We could go back to the use of spondyloschisis; it more accurately describes the etiology of the condition in most cases, but not all. Also, it is difficult to spell and pronounce. A purely descriptive term could be used, like *spondylo-hiatus* or *spondylo-interruptus.* A simple and less drastic answer would be to use "separate neural arch" (SNA), making it very clear that the separation referred to need not be complete.

Finally, how do we view the classic picture described here—stress-fracture spondylolysis and spondylolisthesis with separated arch? Should it be called "pathology," an unfortunate cost of erect posture and bipedal locomotion, or could it represent a clever adaptation to evolved hominid status, the replacement of a rigid connection in the lower back with a much more flexible one? We have been able to trace spondylolysis back several thousand years now, but when, one wonders, will we discover the fossil remains of a hominid who was among the very first to achieve this adaptation?

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